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DEFLECTION EFFICIENCY OF SELF-TRANSDUCING, SELF-SENSING CANTILEVERS SUITABLE FOR FAST-AFM, SCANNING PROBE LITHOGRAPHY AND ARRAY OPERATION

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The maximum imaging speed of current atomic force microscopy (AFM) is determined by the mechanical properties of the cantilever (spring constant, effective mass) as well as the damping induced by the surrounding medium (e.g. air or water). Current high speed AFM systems are able to achieve 40 fps at 200 nm scan size [1]. One of the solutions of increasing scan speeds beyond this limit is parallel operation of single cantilevers in an array configuration [1]. In conventional AFMs, the tip displacement is detected optically based on laser deflection methods. This technique involves optical components and their precise mechanical alignment. An additional technical limit in high speed and high precision metrology processes can be the weight of the optical system, namely in case of that a top-scanner is used [2]. The AFM array configuration further requires an individual excitation and sensing mechanism, which makes the conventional method not applicable.

The Rangelow group [3] has developed and fabricated an alternative cantilever with an integrated actuator and sensor, based on a piezoresistive Wheatstone bridge and bi-material actuator, first integrated in 1996. Due to the individual sensing and actuation ability of the cantilever the scan speed of the AFM process has been increased by an order of magnitude over the standard AFM [4]. A significant improvement in the performance of such cantilevers in respect to deflection sensitivity and temperature drift compensation has been achieved by using an integrated Wheatstone bridge configuration [5]. The thermo-mechanical noise floor of our cantilevers is estimated to 89 fm/Hz^{½} [6]. With this technique today, the overall noise floor of the piezoresistive detection scheme is typically in the range of 10^{-3} to 10^{-4} Å/Hz^{½}. The current version of the active AFM cantilever is depicted in Fig. 1. A detailed overview regarding the fabrication and cantilever types can be found in [3].

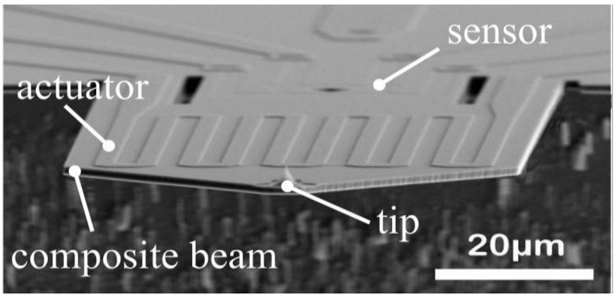

Figure 1: Alternative AFM concept of a composite, active cantilever with thermo-mechanical actuator and piezoresistive sensor.

Applications in lithography and AFM arrays necessitates large displacement and amplitude ranges. Additionally, to further increase the precision of the process, a detailed knowledge of the tip motion based on the indirect sensing is required. Thus, a composite model has been derived, incorporating sensing and actuation mechanisms. Based on an Euler-Bernoulli beam model and Fourier heat conduction, the equation of the discretised coupled thermoelastic system can be derived to:

$$\begin{aligned} \boldsymbol{J}_1\ddot{\boldsymbol{q}}_w &= -\boldsymbol{J}_2\dot{\boldsymbol{q}}_w - \boldsymbol{J}_3\boldsymbol{q}_w + \boldsymbol{J}_4\boldsymbol{q}_\theta + \boldsymbol{F}_{TS} \\ \boldsymbol{J}_5\dot{\boldsymbol{q}}_\theta &= (\boldsymbol{J}_6 + \boldsymbol{J}_7 I^2)\boldsymbol{q}_\theta - \boldsymbol{J}_8\dot{\boldsymbol{q}}_w + \boldsymbol{J}_9 I^2 + \boldsymbol{J}_{10}U_s^2 \end{aligned}$$

All $\boldsymbol{J}_i$ are constants, $\boldsymbol{q}_w$ and $\boldsymbol{q}_\theta$ are the time dependent amplitudes of the mechanical and thermal system, respectively. The excitation current is I and U_s is the supply voltage of the Wheatstone bridge sensor configuration. $\boldsymbol{F}_{TS}$ represents the tip sample force (derived from a Lennard Jones potential). The mechanical and thermal system is coupled through $\boldsymbol{J}_4$ and $\boldsymbol{J}_8$, which are defined by the mechanical and thermal material properties of the different beam layers. Thus, the governing equations describe the actual physical principles of excitation and sensing.

With a selected parameter set (typical for AFM operation), a first analysis revealed deflection ranges up to 100 μm. Figure 2 shows a numerical integration of the governing equations with an excitation at half of the first natural frequency (bending). At 3.4 ms a direct current (DC) has been applied to the actuator, changing the static displacement about 10 μm.

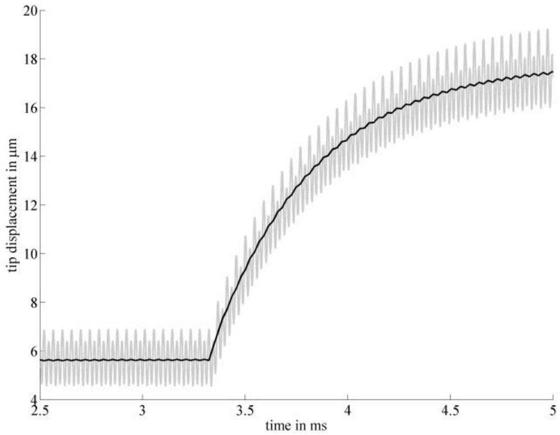

Figure 2: Numerical integration of the governing equations with an excitation at half of the resonance frequency.

An experimental validation of these findings has been done using a similar cantilever as depicted in Fig. 1. In contrast to the model, the beam is pre-deformed by 52.7 μm, as can be seen in Fig. 3 (left). Applying a constant current to the heater, a displacement of 9.96 μm can be achieved. Such a DC adjustment is used to control the constant force/distance operation in e.g. AFM scan. Depending on the beam's geometrical composition, the cut off frequency of the thermal system is around 10 kHz, which determines the speed of the scan process.

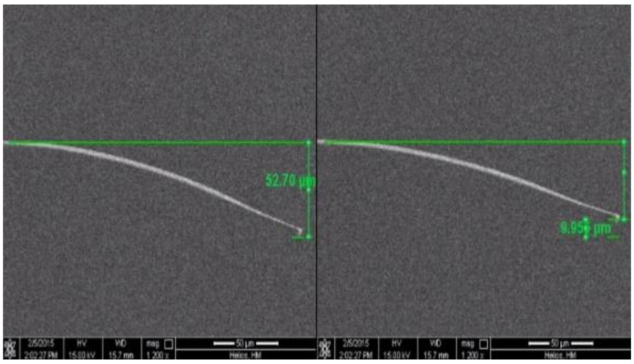

Figure 3: (left) SEM image of pre-deformed self-transducing, self-sensing cantilever; (right) 9.96 μm tip displacement of a 350 μm-long cantilever (f_{res}=45kHz).

Therefore, the presented self-transducing and self-sensing cantilever concept is suitable for a fast AFM scan process [7] as well as its integration in an array configuration. With a static displacement of 10 μm together with an achievable thermal cut off frequency of 10 kHz, the thermal actuator is used instead of the commonly used piezoelectric positioning stages for z axis control. The static deflection and a feedback loop with the piezoresistive sensor yields a faster controller for a constant distance between tip and sample. With this setup, the cantilever has been used for scanning probe lithography, creating features with dimensions of 50 nm width and 5 nm depth [8].

For future research, the model will be used to predict the motion of the cantilever's tip based on a measurement of the piezoresistive sensor. This indirect measurement relies on the mechanical stress at the beam's fixed end, which can vary between different operation modes (e.g. manipulation, multi-mode AFM). This renders a direct conversion from sensor voltage to tip displacement difficult and yields the need for a model based estimation.

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